Inverse Problems in Optical Remote Sensing of Coastal Waters

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LONG-TERM GOALS

The long-term goal of the Project is to develop robust inversion algorithms to extract estimates of the optical and physical properties of sea water layers, the sea floor, and the sea surface from LIDAR (Light Detection and Ranging) returns, and optical imagery of the ocean bottom and depths and to improve the quality of images of subsurface objects collected over the sea.

OBJECTIVES

The project objectives are: 1) to develop new models of water, bottom, and surface returned LIDAR signals and to develop new mathematical inverse techniques to extract from actual or simulated LIDAR returns the inherent optical properties of water (IOP) and to estimate parameters of internal waves (IW) from IW-induced disturbances of IOP stratification; 2) to develop theoretical mathematical techniques and experimental procedures to improve the quality of passive images of the coastal sea floor by correcting distortion due to light refraction through rough sea surfaces; and 3) to develop mathematical techniques for the retrieval of the quantity of optically active materials (chlorophyll, dissolved organic matter, and sediment) from the color spectrum of sea water optical returns.

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APPROACH

The project is broken into three tasks: 1) the determination of IOPs of sea water and parameters of IW using LIDAR soundings; 2) the correction of surface wave refractive distortion; and 3) the estimate of optically active material (OAM) content from the spectrum of returned light.

Our approach in accomplishing the first task is to improve IOP estimation from LIDAR returns by using correlations between various IOPs and by jointly processing the signals from two or more sensors with different viewing angles. The approach involves development of specific algorithms for determination of difficult-to-measure IOPs from easily measured IOPs by taking advantage of observed IOP correlations, and evaluating the accuracy of these algorithms. We also develop other algorithms not using IOP correlations to independently determine the backscattering and scattering coefficients using signals from several sensors, as well as mathematical models of LIDAR images of the internal waves. The basis for these models is given in Dolina et al. (2005). Using known LIDAR signal equations and analytical models of internal waves (IW), we develop a model and an algorithm for numerically modeling the IW-induced LIDAR image generated by several lower order IW modes. These are used to analyze the possible methods to solve the inverse problem and determine the IW parameters from their LIDAR images.

Our approach in accomplishing the second task follows the theory developed in 2000-2005 and generalized in the monograph of Dolin et al. (2006). Here the mathematical background for the image transfer through a rough sea surface under natural illumination is presented as the basis of an advanced sea bottom imaging model. This model may be used to choose a flight strategy (e.g. direction with respect to waves and sun, etc.) to decrease the image noise due to fluctuations of radiation produced by the action of surface waves on the upwelling light reflected from the bottom, backscattered in the water body, and reflected from the surface. However even the best flight strategy can not remove image distortion due to random light refraction through the surface slopes. Thus our approach is to develop a method to correct wave-induced distortion in images of the coastal sea bottom. Our method involves obtaining surface slope information from multispectral surface images and developing algorithms that use the full information about two-dimensional anisotropic surface roughness to correct bottom images. We also consider how to correct image distortion when only partial information about sea surface relief and slope is available and to analyze image retrieval quality as a function of the completeness of the amount of surface relief information. The basis for this research is given in Dolin et al. (2003, 2004, and 2005). Our approach also involves constructing laboratory equipment and conducting experiments on the retrieval of images distorted by surface waves.

Our approach in accomplishing the third task is to develop an algorithm computing the best linear estimate of OAM, e.g. phytoplankton, sediment, and yellow substance, from radiance spectra measured by multi- or hyperspectral sensors located at arbitrary heights above the sea surface. This algorithm takes into account sensor noises and maritime atmospheric variations. Earlier versions of this approach were presented in Levin et al. (2005). The approach involves estimating the accuracy of OAM retrieval and an analysis of possible ways to increase retrieval accuracy by varying sensor parameters and expanding a priori information about observational conditions.

WORK COMPLETED

Work completed for the first task consisted of the comparative analysis of two different approaches to the problem of retrieving the IW's pycnocline field from its lidar image. The first retrieved the parameters of the IW field from the relative variation of the lidar return and non-perturbed depth profile of the attenuation coefficient $c(z)$ without using an IW model. The second approach used pycnocline parameters to reconstruct a mode model of the IW field. This model used a small number of IW parameters, i.e. the mode number, its amplitude and wavelength. We showed that the solution of the inverse problem using the second approach allowed a significant reduction in the required accuracy of the $c(z)$ profile.

Work completed for the second task was mainly aimed at experimentally testing the adaptive methods of image correction previously suggested. The idea of these methods is to simultaneously register images of an underwater object and of the sea surface through which it is viewed in different spectral ranges and then to remove image distortion of the object using information on the surface slope contained in the surface image. We investigated two adaptive observation procedures. The first one, the "glitter method", is based on separating the instantaneous image fragments that are viewed through elements with zero or some other given slope. The complete distortion-corrected image is then formed by an accumulation of these fragments. The second procedure follows Dolin et al. (2003, 2004, and 2005) and retrieves the true underwater object image from a random realization of the distorted image and image of the surface area through which the object is viewed. Investigations of the glitter method included a laboratory experiment performed using a new experimental technique developed and constructed during the previous stages of the project. During the second stage of the project a methodology and an algorithm for processing images was developed so that after processing and accumulating, a corrected image of the test-object was obtained having white and black strips of constant width. During this stage of the project the algorithm developed and the experimental procedure was applied to a black and white striped underwater test object with strips of varying width. Use of such a test-object allowed the analysis of how various spatial frequencies could be corrected and compared to the corrected image resulting from signal accumulation without correction. To check the second observation procedure, a specific laboratory installation was designed and built, computer codes for image processing were written, and a series of experiments was carried out. The experiment shows that in principle the object's image can be retrieved from a single distorted color photograph, if it is possible to spectrally separate the object and surface images. Besides, we investigated theoretically how backscattered signal can be used to compensate the refraction distortion of bottom images formed by pulsed laser scanning imaging system.

The third task used the spectrum of returned light to estimate the content of optically active materials (OAM), while accounting for sensor noise. During a previous stage of the project we had computed the regression coefficients and residual variance of OAM retrieval for a hyperspectral sensor collecting data at an arbitrary altitude over the sea surface. The computed accuracy of OAM retrieval was averaged over the concentration range employed in the simulations. During this stage of the project we carried out numerical experiments to study how the retrieval accuracy varied with concentration range. Using a database containing 1000 simulated radiance spectra with corresponding "true" concentrations of phytoplankton, sediment, and organic matter (C, X and Y respectively) we computed the first two moments of their joint distributions and found the regression coefficients of the equation for the best linear estimate of OAM concentration. Then we generated another 100 random samples, retrieved the concentrations C, X, or Y, and found how the retrieval accuracy changed across the concentrations' range. Another numerical experiment was done to determine how the retrieval accuracy could be improved if additional a priori information about the range of C in the region of observations was available and the range of C could be narrowed down.

RESULTS

For the first task early in the project we had developed an analytical model of the lidar image of the IW's pycnocline and showed that the IW image was the superposition of two images, a reflected image and a shadow or projected image. The first image represented the disturbance of the backscattering coefficient profile in the IW field, while the second one represented the disturbance of the optical thickness of the water layer where the IW disturbed the IOP's natural horizontal homogeneity. We proposed an algorithm for the retrieval of the IW field from the relative variations of the lidar return and the undisturbed $c(z)$ profile. An analysis of this algorithm done during this final stage of the project shows that it can be used for depth ranges with rather large gradients of the beam attenuation coefficient, $c(z)$, when the $c(z)$ profile is known with great accuracy. However, as we have shown, the problem of the IW field retrieval can be solved using rather crude IOP data, if we could calculate the vertical structure of IW modes and construct their dispersion characteristics based on pycnocline parameters. This approach reduces the problem of IW field retrieval to determination of the mode number, its wavelength and amplitude. However, the required accuracy of the $c(z)$ profile in this case is subsequently reduced. In particular, if a thin turbid layer is situated in the pycnocline domain, the IW field can be completely retrieved from data on deformation of this layer without using data on IOPs, when the lidar sees this layer well. Computer simulations of the IW shadow images showed that their contrast (K) depends slightly on the detailed structure of the $c(z)$ profile. This can be seen in Fig. 1, where two different profiles of $c(z)$ are shown in the left part of the figure, while the right part of the figure shows for these two profiles the computed contrast of the shadow image of the first IW mode as a function of its amplitude. Our research demonstrated that the registration of the shadow structures in the lidar images of IWs allows the retrieval of the IW field from the lidar return based on often crude data for the depth profiles of water density and attenuation coefficient.

The second task was concerned with correcting image distortion due to the refractive effects of a wavy water surface. Algorithms to correct images distorted by waves were developed and tested, with their efficiency confirmed by laboratory experiments. In the experiments on the first observation procedure mentioned above, the "glitter method", the image correction was done for a test object with strips of varying width. Some results are shown in Fig.2. The left upper box (*A*) shows the test-object image obtained through a flat calm water surface. The right upper box (*B*) is an image of the same test-object obtained through a wavy air-water interface with an exposure time of 1/400 s. As may be seen, the image is highly distorted with almost no apparent information about the spatial structure of the original test-object. The lower left picture (*C*) is the image accumulated during 5 seconds without any correction. The lower right box (*D*) shows the corrected image after using our image processing method on about 300 images. (The brightness of the white stripes would be more enhanced with more images processed.) As may be seen, the outline of the restored image is rather close to the undistorted initial test-object image. One can also see that accumulation without correction (*C*) even though it provides some improvement over the image obtained with the uncorrected short exposure image (*B*) at low spatial frequencies, results in poorer image quality compared to the corrected image, especially for the smaller widths of the object strips. Here the high spatial frequency information of the original test-object is lost.

The second adaptive observation procedure requires full information about the slopes inside the water surface area within the receiver's view. This procedure requires that an underwater object or sea bottom should be photographed in such a way that solar glitters do not appear in the frame. The image of the waves should be the specular reflection of the radiance gradient of the specular sky area. This makes the problem of retrieving the surface slope data from its image much easier. Thus the experiment testing this procedure was carried out using the laboratory installation shown in Fig. 3. This installation includes a tray with water, a fan inducing surface waves, and an extended light source simulating the specular sky. The latter was made in the form of a rough non-uniformly illuminated screen with an almost linear apparent radiance in the *x* direction. To separate the images of the submerged object from that of the surface we placed a self-luminous object – a blue light source with a striped mask at the bottom of the tray, while the water surface was illuminated by red light. The red component represents the wave image, while the blue one represents the distorted object image. Specific algorithms were developed for determining the spatial slope distribution and image correction. Sample results of these experiments are shown in Fig. 4. The left column presents three random realizations of slope distribution along the *x* – direction determined from photographs of the wavy surface and of the sky simulator reflected in the flat water surface. The middle and right columns are the distorted and retrieved images respectively.

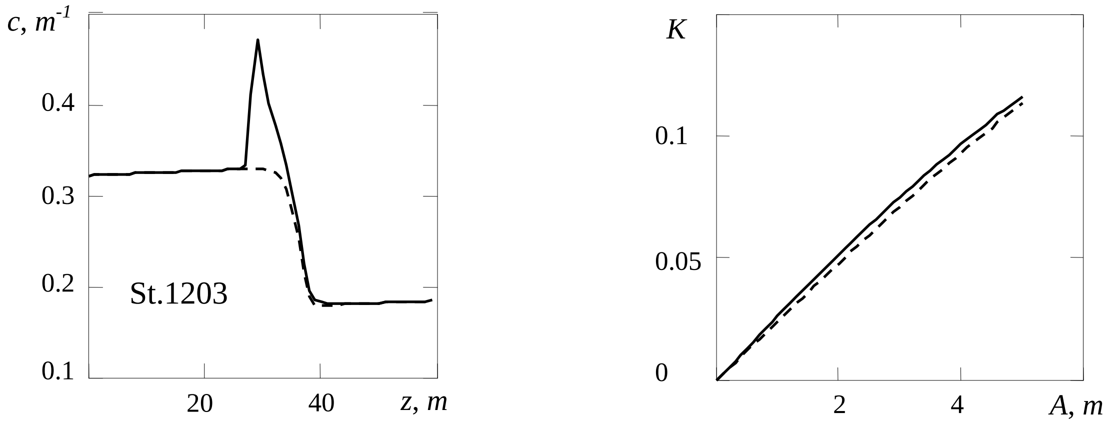
Note that although the procedures used in the laboratory experiments can't be immediately applied to observations through a real wavy sea surface, the possibility of correcting images of underwater objects distorted by waves has been demonstrated. It also highlights important issues that must be considered, if and when an in situ experiment is undertaken.

We investigated the possibility of using the water-backscattered radiation from a bottom sounding airborne imaging lidar to determine the surface slope at the point where the laser beam intersects the surface. We showed that the refraction angle of the beam can be determined using receivers whose sensitivities vary linearly over their field of view. Equations were derived to estimate the statistical mean and variance values of this refracted angle. We demonstrated that the proposed algorithm improves lidar imaging. Numerical examples with reference to typical marine conditions were given.

Task 3 was concerned with the problem of retrieving the concentrations of OAM from ocean radiance spectra. Results of a numerical experiment to investigate how retrieval accuracy varies across the concentration range can be seen in Fig. 5. The figure shows the relationship between modeled ("true") and retrieved ("estimated") values of log-concentrations of phytoplankton, sedimentary, and organic matter (C, X and Y respectively) for the case of shipboard observation. One can see that the absolute retrieval errors are approximately constant across the concentration range. To determine how the retrieval accuracy could be improved if additional a priori information about the range of phytoplankton concentration C in the region of observations was available, we repeated the computation of retrieval accuracy for several different ranges of C. This showed that a priori information can markedly improve the accuracy of concentration retrieval.

IMPACT/APPLICATIONS

This work has applications in shallow water bathemetry, bottom mapping, and search by optical imaging methods. Airborne imagers are more economical and efficient in collecting data from shallow waters, but may have wave induced refractive surface distortion. One of the tasks here shows great potential in mitigating such distortive effects. Additionally laser sensing of internal waves and optical gradients can be applied to understanding the energetics of the near surface waters. Finally the ability to derive inherent optical properties from apparent optical property data such as Secchi depths can prove invaluable in circumstances where the US NAVY must operate imagers and LIDARs in regions with limited data on inherent optical properties.



a *b*

Fig. 1. a) Actual c(z) profile on the station 1203 in the Barents Sea (solid line) and the smoothed profile without the turbid layer (dotted line); b) Computed contrast K of the shadow image of the first IW mode as a function of its amplitude A for the actual (solid line) and smoothed (dotted line) c(z) profiles. The actual pycnocline parameters for station 1203 was used in our computations. Fig. 1b demonstrates a weak dependence of the contrast of IW shadowy image on the thin layer structure in the c(z) profiles.

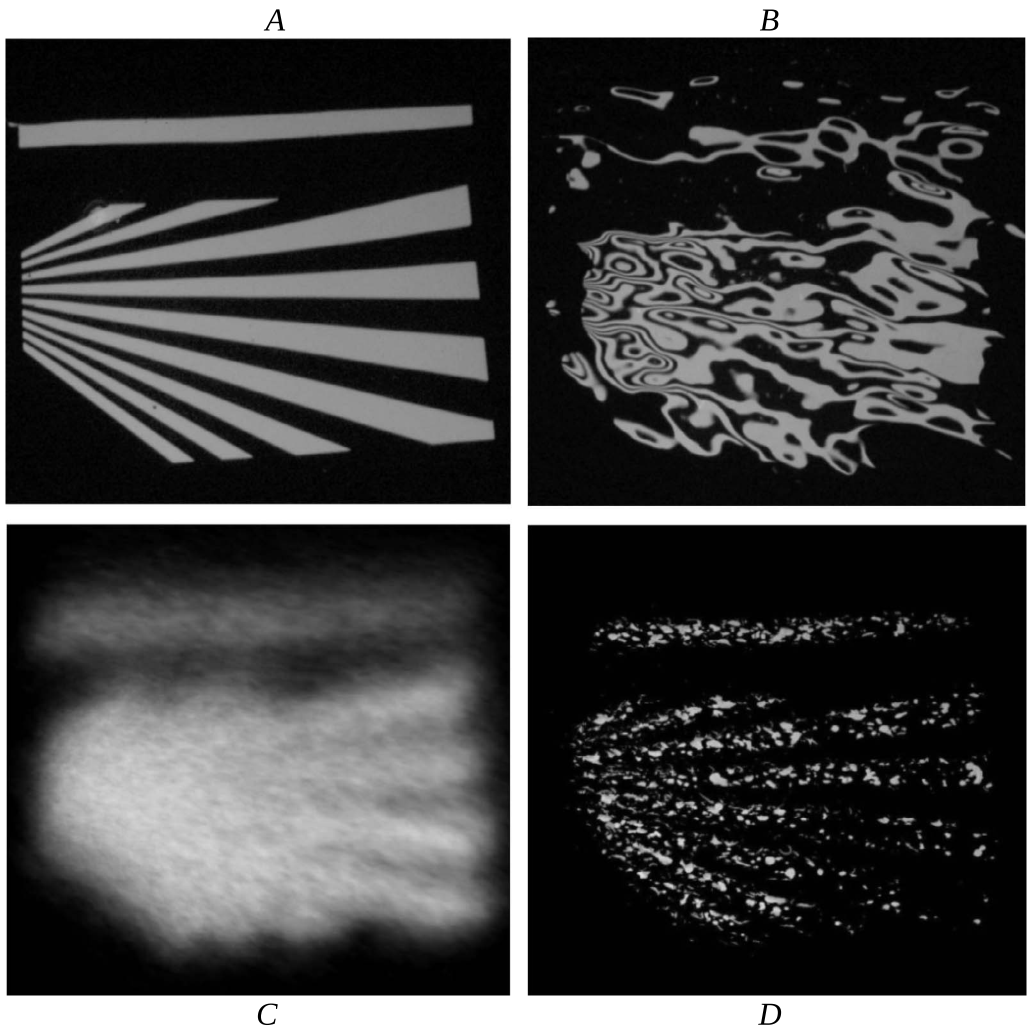


Fig. 2. Images of a test object with varying width of the strips: original image (A), single instantaneous image (B), accumulated image without correction (C), corrected image (D).

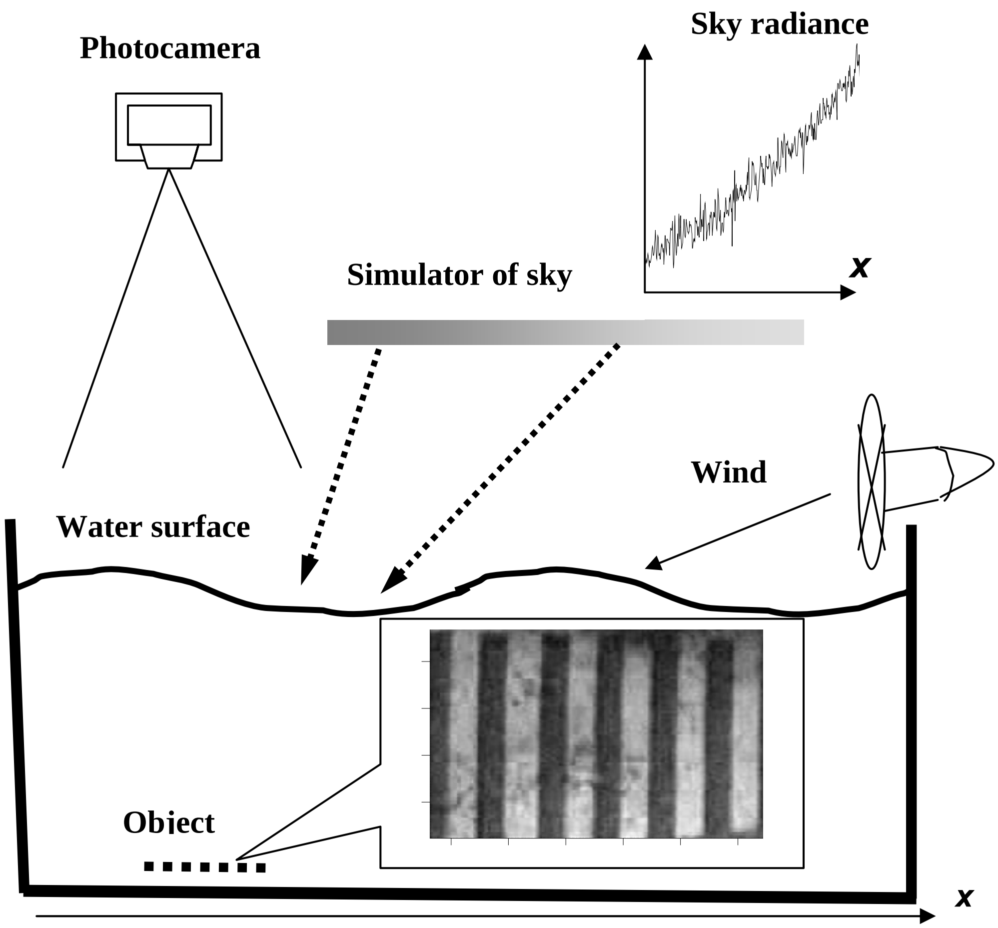


Fig. 3. Schematic diagram of laboratory experiment on correcting an image distorted by surface waves (the second observation procedure, using the gradient of the specularly reflected sky).

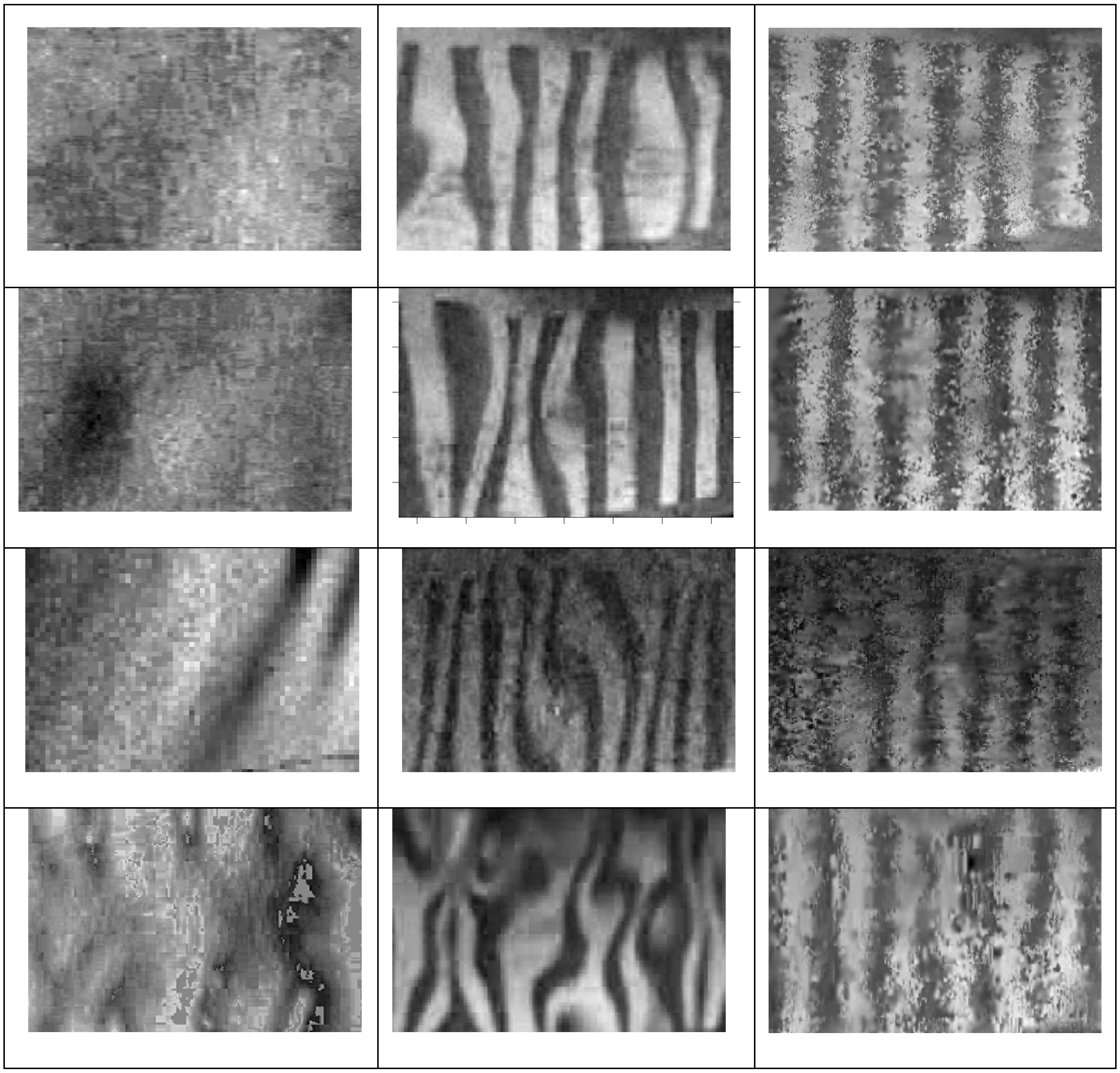


Fig. 4. Examples of correction of the instantaneous images of the test-object shown in Fig. 3: two-dimensional surface slope distributions along x – direction in the moment of object photographing retrieved from surface images (left column); random realizations of the distorted object image (middle column); corrected images (right column).

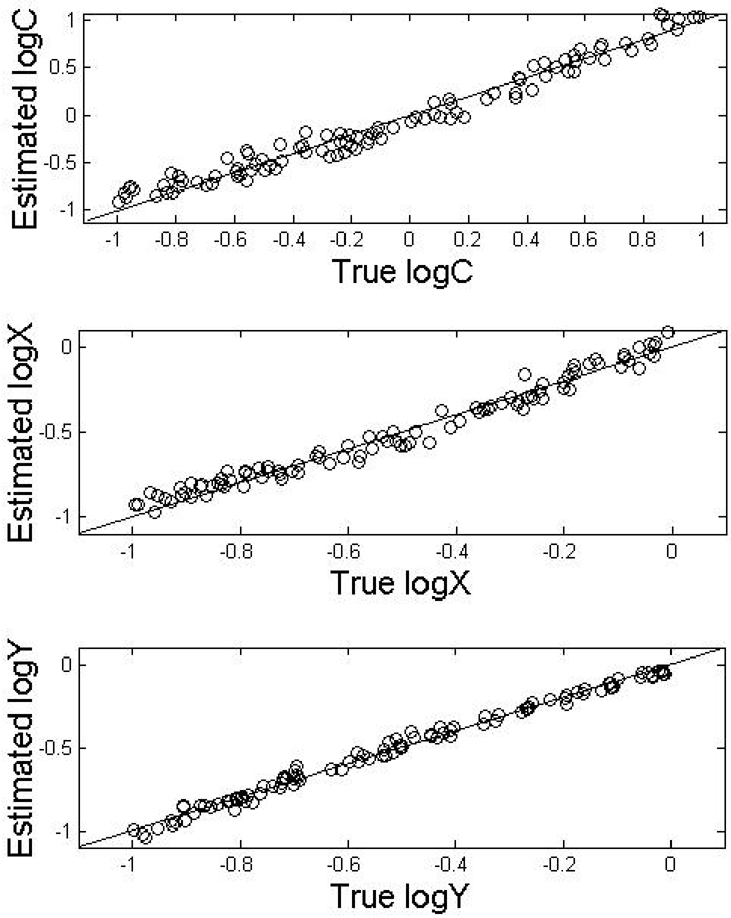


Fig.5. Dependence between modeled ("true") and retrieved ("estimated ") values of concentrations of phytoplankton (C ***), sediment (*** X ***), and organic matter (*** Y ***) for the case of shipboard observations.***

RELATED PROJECTS

None.

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HONORS/AWARDS/PRIZES

L.S. Dolin was awarded the S.I. Vavilov Honour Medal from D.S. Rozhdestvensky Optical Society in 2006 for outstanding achievments in the optics of turbid media.

I.M. Levin was awarded the 1-st prize for the best scientific publications in 2006-2007 by P.P. Shirshov Institute of Oceanology for publications 1, 2, 5-7, 10, 15 listed above.